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The data set described in this report was collected on 150-154 Ma oceanic crust during the DARPA/Navy Low Frequency Acoustic Seismic Experiment (LFASE). This is some of the oldest lithosphere remaining in the modern oceans. The experiment used an array of airguns as a source and ocean bottom seismographs (OBS) and a borehole array as receivers. Our final model of the seismic structure of oceanic crust at the LFASE Site was obtained using travel times along with general characteristics of amplitudes and waveforms of the crustal P-wave arrivals. In this paper we discuss the results of the LFASE seismic data interpretation and compare our results to those of Purdy (1983) for 140 Ma lithosphere.

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LFASE REPORT

Crustal Study

July, 1993

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ABSTRACT

The data set described in this report was collected on 150-154 Ma oceanic crust during the DARPA/Navy Low Frequency Acoustic Seismic Experiment (LFASE). This is some of the oldest lithosphere remaining in the modern oceans. The experiment used an array of airguns as a source and ocean bottom seismographs (OBS) and a borehole array as receivers. Our final model of the seismic structure of oceanic crust at the LFASE Site was obtained using travel times along with general characteristic of amplitudes and waveforms of the crustal P-wave arrivals. In this paper we discuss the results of the LFASE seismic data interpretation and compare our results to those of Purdy (1983) for 140 Ma lithosphere.

INTRODUCTION

In the last two decades scientific and strategic interests have accelerated the study and understanding of the geological structure of the Earth's ocean basins. Wide-scale geological-geophysical experiments have been performed to investigate the composition of the oceanic crust, determine the internal structure of the upper mantle and the sedimentary layer and to estimate the amount of mineral resources. Important efforts have been made to understand the dependence of the observed differences in the seismic structure on spreading rate (e.g., Reid and Jackson, 1981), tectonic regions (e.g., Klein and Langmuir, 1989) and other factors (e.g., Spudich and Orcutt, 1980). To understand the mechanism of crustal processes, it is important to recognize and to map the systematic changes in structure that can provide useful information for the new model. However, there is a lack of homogeneity in experiment locations. For instance, only a few experiments in the last ten years were performed on old (>110 Ma) oceanic crust, using current state-of-the-art instrumentation, data analysis, and interpretation techniques.

The primary source of data on seismic structure of oceanic crust is provided by seismic reflection and refraction experiments. The data set described in this paper was collected on 150-154 Ma oceanic crust during the DARPA/Navy Low Frequency Acoustic Seismic Experiment (LFASE). Figure 1 shows the location of the LFASE Site. The experiment used an array of airguns as a source and an ocean bottom seismograph (OBS) as the receiver. The main purpose of this study was to determine the structure of the some of the oldest oceanic crust available in the modern (present day) oceans as accurately as possible from the observed data set. In this report we discuss the results of the LFASE seismic data interpretation and compare our results to those of Purdy (1983) for 140 Ma lithosphere.

GEOLOGICAL SETTING

From a previous geological study by Bryan et al., (1980), the eastern continental edge of the Northern American continent has been determined to abut the oldest lithosphere remaining in the modern oceans. Essentially the Blake-Bahama Basin is an abyssal plain, which lies below 5000 m of water. The Basin is bordered by the Blake-Bahama Outer Ridge to the north and east and the Blake Escarpment to the west and south. Although the continental rise to the north of the basin is underlain by several kilometers of sediment, the basin only contains 1700 m - 2500 m of sedimentary strata (Bryan et al., 1980). Based on magnetics measurements (Bryan et al., 1980), the Blake-Bahama Basin lies within the Jurassic quiet period and away from the major fracture zones. The presence of small amplitude magnetic anomalies in the Blake-Bahama Basin (Sheridan and Osburn, 1975), along with the other magnetic studies of the Jurassic quiet zone in the western Atlantic and Pacific oceans (Barret and Keen, 1976; Larson et al., 1978), indicates that oceanic basement blocks of alternating polarity exist west of anomaly M25 (Fig. 2). A spreading rate of 38 mm/yr was estimated from anomalies M22 through M25. Basaltic ocean crust at the DSDP 534 A Site (where the LFASE experiment was conducted) is believed to be about M-28 age (Sheridan, 1980), which, by extrapolation, is estimated to be on the order of 150 to 154 Ma (Fig. 3).

FIELD EXPERIMENT

In August of 1989, the John Hopkins University Applied Physics Laboratory (JHU/APL), the Institute of Geophysics and Planetary Physics (IGPP) of the Scripps Institution of Oceanography, the Marine Physical Laboratory (MPL) of the Scripps Institution of Oceanography, the Naval Oceanographic Research and Development Activity (NORDA), Science Applications International Corp. (SAIC) and Woods Hole Oceanographic Institution (WHOI) conducted the Low Frequency Acoustic Seismic Experiment (LFASE) in the western northern Atlantic ocean near Deep Sea Drilling Project (DSDP) borehole 534A (Fig. 1). Three component digital Ocean Bottom Seismographs (OBSs) were used as the receivers and airguns were used as the source. OBSs from IGPP and NORDA were placed on two orthogonal lines extending in the NE and SE directions from the borehole with the closest instrument being within 100 m from the hole and most distant within 4500 m (Fig. 4). This configuration allowed the collection of several refraction profiles during one "pass" of the ship in addition to increasing the probability of recording data in case any instrument should fail. During the LFASE experiment the first ship-supported wireline reentry of a DSDP borehole and first deployment of a vertical seismic array beneath the seafloor were achieved. Therefore, along with the seismometers placed on the seafloor, signal and noise data were also recorded by the borehole array. Unfortunately, the clamping arm of the second satellite of the borehole array failed to extend. However, data from the seismometers at 10, 70 and 100 m below the seafloor were of excellent quality (Fig. 5) and have somewhat lower noise (and signal) levels compared to the OBSs.

Receiver. One of the primary objectives of the LFASE experiment was to test a new OBS designed by the IGPP group. The general view of the OBS is shown in Figure 6. This unit is equipped with timed and acoustic release mechanisms. The IGPP OBS consists of one vertical seismometer (resonant frequency of 1 Hz) to record compressional P-waves, two horizontal seismometers to record the S_x and S_y shear waves and a

hydrophone. The useful frequency range of the seismograph is 50 mHz to 30 Hz. The seismic data were sampled at 8 msec intervals and data were recorded continuously on Exabyte® recorders. The lifetime of the units for this experiment was 30 days. These new OBSs contained a microprocessor to control all OBS functions, while previous units were strictly hardware controlled. An entirely new recording system was developed and implemented during the LFASE experiment. Compared to the older reel-to-reel data recording medium with a maximum capacity of 16 Mbytes, the new instruments contained a 8 mm helical-scan data cassette recorder (Exabyte®), with a memory capacity of 2.3 Gbytes. Digitized data were first stored in RAM and once the accumulation exceeded 4 Mbytes, the cassette recorder was turned on and the RAM contents were transferred to the tape. A Sea-Scan® clock installed in the OBSs provided timing accuracy between a GOES clock on the ship and the OBS's clock on the order of a few milliseconds. For further information on SIO OBS design see Willoughby et al., 1993.

Source. Two NW-SE profiles were fired with a small array consisting of one 300 and two 550 cubic inch airguns. The total capacity was 1400 cubic inches and the guns were towed at approximately 7 meters depth. A hydrophone streamer towed behind the ship at 10 m depth was used for shot break control. The shot interval was 1 minute and the distance between each shot was approximately 100 m. The geographical position of shots and receivers was determined by the LORAN C navigation system. The absolute error of the LORAN C position was 180 m. (D.Bibee personal communication).

Observations along one circular and four linear profiles with different azimuthal orientations (Fig. 7) provided the most complete information on the seismic structure of oceanic crust and anisotropic properties for this region. Two NW-SE linear profiles were 40 and 24 km long while two NE-SW trending lines extended up to 24 and 28 km. The radius of the circular profile was 10 km.

DATA PROCESSING AND CORRECTIONS

The raw OBS data were converted from the LFASE OBS digital tape format to standard SEGY format files. Geographical positions of the source vessel, the R/V Lynn, measured by the LORAN-C system, were used to determine the distances between the sources and the receiver. These distances were checked and later corrected using direct water wave travel times. Analog acoustic 12 kHz and 3.5 kHz echo-sounder records were used to determine the water depth at the LFASE site. The water velocity was assumed to be 1500m/s for these data. Original records were digitized by hand at 3 minute intervals. This sampling interval was sufficient since the topography is relatively flat. Depths were assigned to the latitude-longitude pairs using the navigation data. During the LFASE experiment a few profiles were recorded using Tovex® explosive as the source. Depth measurements at each explosive shot location were added to sonar records to construct a bathymetric map (Fig. 13). This chart was used to perform bathymetric corrections.

A zero-phase band-pass filter between 5 and 20 Hz was used in increase the signal-to-noise ratio of the data collected. Figures 8 and 9 plot time series before and after filtering, respectively. The data are displayed with the travel-time reduced by 6.5 km/sec. Data without the reduction velocity and filter application are plotted in Fig. 10.

Navigation correction procedure. Since the OBSs are free-fall devices their actual positions on the seafloor will differ from their launch positions and the absolute error of the navigation system adds some uncertainty to the instrument positions. The OBS location was corrected using the direct water-wave arrivals from both the azimuthal and circular profiles within 10 km of the instrument. Since the number of observations are greater than the number of model parameters, we solve this problem in a least square sense (Lawson and Hanson, 1974), using a method similar to that in an earthquake location problem. This resulted in corrections of the OBS, Karen, position by 285 m south and 555 m west (Fig. 11). Figure 12 shows the comparison of travel-time picks vs. uncorrected and corrected

ranges. There is still some scatter in the plot due to error in the picking routine and the error in the navigational system, but the bulk location anomaly is resolved.

A few words about mathematical background of the relocation method. The relative OBS location can be calculated by solving a linear inverse problem. The forward equation can be written:

$$\mathbf{Gm} = \mathbf{d}, \tag{1}$$

where **G** is a partial derivative matrix of the travel-time arrivals with respect to X, Y and Z coordinates, **d** is an array of residuals or differences between the picked and theoretical times of the direct water waves. The theoretical time is calculated assuming a homogeneous medium. The model **m** is a 3x1 vector with Δ X, Δ Y and Δ Z as the elements, which are the corrections in the starting model or OBS location, which give a better fit to the data. The number of arrival time observations is greater than the number of model parameters, i.e. the problem is overdetermined, and we solve for **m** in a least square sense. This operation is repeated until the model converges and hence minimizes the total misfit to the data.

Topographic corrections. To produce a topographic map of the region, a 2-D thin plate spline interpolation technique was applied to the latitude, longitude and depth triples, obtained from echo-sounding records and explosive shot ocean depth measurements. Figure 13 displays this map along with the data points from which it was produced. Water column velocity data from CTD's and XBT's are shown in Figure 14 and all depth measurements were corrected using this water column profile. These corrections increased the measured depths of the seafloor on an average by about 50 m. The depth data were gridded and written in the URI SEABEAM matrix format. The depth of the seafloor under each airgun shot was calculated by interpolation between the four grid points of the map in the closest vicinity of the airgun shot and the final ocean floor depth for each airgun shot was obtained by a linear weighted average. To remove the seafloor topography effect superimposed on the signal from the crustal structure variations, the water wave travel time was calculated using the topography and then subtracted from the crustal arrival time (Fig.

15), so that any variations in the travel time curve would reflect only the crustal structure anomalies (Purdy, 1982a).

DATA MODELING

In order to model data, accurate arrival time picks were needed. In this study we utilized only the airgun data recorded by the vertical seismometer. Our final model was obtained by matching arrival time, amplitude and waveform of crustal phases of the synthetic seismograms to the real data as closely as possible.

Travel-time picking. The high quality vertical component records of OBS Karen were used to pick the first arrivals of the different phases of the compressional wave. They were picked by hand with the interactive picking program SENPICK. This picking program, written by Dr. Mark Burnett, displays ten traces from the SEGY seismic record section simultaneously and allows user to choose the time interval and the shot numbers to be displayed. In addition, the user can page up and down through the record section. The zoom-in (via the EXPAND command) feature increases accuracy when picking arrivals. The time-shifting tool allows individual waveform alignment. The automatic picker tool, built into SENPICK, is useful when seismograms have a high signal to noise ratio.

Modeling. Determination of the P-wave velocity structure involved delay time inversion of the OBS data. The "picks" in the T-X domain were transformed into the τ-p domain, where the inverse problem can be solved uniquely by estimating the smoothest model (Kappus et. al., 1990). Initial modeling of the travel-time data, using this smoothest model as a starting model, was performed using the ray-tracing routine "KINE" and the interactive "Macmodel" program. The "Macmodel" routine allows the user to simultaneously display the velocity model along with calculated (by this program) and observed t-x and τ-p curves. This program was very helpful for the model modification in the early stages of the travel-time fitting. Once travel-time curves were matched to a reasonable level, synthetic seismograms were calculated using the WKBJ algorithm (Chapman, 1978); the Green's functions were convolved with an appropriate source function. We fine tuned the model to match the amplitude and waveform of the synthetics to the data as closely as possible. Our final model of the seismic structure of oceanic crust

at the LFASE Site (Fig. 16) was obtained, therefore, using travel times along with general characteristic of amplitudes and waveforms of the crustal P-wave arrivals. There are some gross trends that occur in the range versus amplitude behavior (Fig. 8). Amplitudes tend to be high between 7 to 12 km, decreasing to smaller levels between 20-27 km (in fact they almost disappear). Another high amplitude branch appears from 29 to 33 km. The true amplitude of the crustal arrivals in the last 5 km of this section (35-40 km) is masked by noise, although arrivals are still visible and were picked for modeling purposes. Comparison of the synthetic seismograms, produced by our model and the observed wavefield are shown in Figure 17. The differences between the real and the synthetic travel times vary between 0.1 to 0.2 msec. This misfit is believed to be due to errors in the travel-time picking, uncertainties in the lateral variation of the sediment thickness, the sampling rate and crustal heterogeneity.

RESULTS, DISCUSSION, CONCLUSIONS

The P-wave velocity model

The final velocity model of the oceanic crust at the LFASE Site, with a total thickness 8.3 km, is characterized by three major layers (Fig. 16): a sedimentary layer, a volcanic Layer 2, a lower crustal layer or Layer 3, and the mantle.

The first, i.e. sedimentary layer, is 2 km thick and has compressional wave velocities increasing from 1.9 km/s to 3.2 km/s. The initial parameters for the sediment units were taken from multichannel seismic-reflection study and sonobuoy measurements by Bryan et al., 1980. Our data set was not able to resolve the sedimentary structure in as great detail because of the lower frequency content in the airgun source and a lower frequency response of the OBS. Therefore, our model of the sedimentary layer shows only the longer wavelength features, but is consistent with the Bryan et al. (1980), results.

In our model, oceanic Layer 2 is 1.23 km thick. It appears as one layer in the observed wavefield, but from the synthetic seismogram modeling, has to be divided into two sublayers: the upper sublayer with a thickness of 0.47 km and increasing velocities from 5.4 km/s to 5.8 km/s and the lower sublayer with velocities from 5.9 km/s to 6.45 km/s and a thickness of 0.76 km. The first sublayer is most likely comprised of the extrusive pillow basalts. Its high gradient can be explained by a decrease in the porosity and crack closure with depth (Spudich and Orcutt, 1980b). The lower layer consists of intrusive sheeted dykes. From previous studies, the variations in the thickness and velocities of oceanic Layer 2 have been noted. Various authors (e.g., Reid and Jackson, 1981, Klein and Langmuir, 1987, Spudich and Orcutt, 1980) made efforts to understand the dependence of these observed differences on spreading rate, tectonic regions, crustal age, porosity, pressure and other factors. The relatively high velocities in the upper part of the second layer of our model are probably due to the extreme age of this crust (150-154 Ma). Young crust is characterized by high porosity in the upper Layer 2 and the presence of

seawater in pores and cracks. During the aging process the crust becomes less porous because of hydrothermal mineral filling of high aspect ratio voids.

Layer 3 in our model is 4.8 km thick with velocities increasing from 6.5 to 7.3 km/s. The observed velocity gradient is smaller (0.1 s^{-1}) in this layer compared to the Layer 2 described above and reflects compositional changes and an increase in pressure (Spudich and Orcutt, 1980).

The crust-mantle transition zone or Mohorovichich (Moho) discontinuity is about 0.1 km thick. The upper mantle is characterized by a P-wave velocity of 7.8 km/s.

Therefore, as a result of this study, a seismic velocity (P-wave) model has been obtained for the oldest (150 - 154 Myr) crust available in the modern oceans. This model probably typifies the deep structure of the oceanic crust in this region and reflects the genesis and evolution of the crust.

Compared to previous results for 140 Myr old crust by Purdy (1983) our model features a thinner crust by approximately 1.5 km (Fig. 18). The upper part of our model has, on average, a higher velocity (by ~ 0.2 km/s) and a higher velocity gradient. The lower part of the two models are quite comparable with almost identical gradients; the total thickness of this low gradient layer is 4.8 km for the LFASE Site and 4.9 km for Purdy's model. The Moho transition zone of the Purdy model for the 140 Myr old igneous crust is characterized by velocities increasing from 7.0 km/s to 8.2 km/s over a thickness of 0.5 km. We estimated this crust-upper mantle transition zone to be 0.1 km thick and have velocities from 7.3 km/s to 7.8 km/s. During the LFASE experiment only one profile extended to 40 km, and is the only profile where PmP is visible. The Pn phase (arrivals from waves turning in the upper mantle), synthetically modeled (Fig. 19), can be observed (large enough amplitude) at distances greater then 50 km, but our profiles did not extend this far.

Purdy and Ewing (1986), in discussing the seismic structure of the western Northern Atlantic, emphasized that there have been too few good experiments performed to

allow characterization of the variability of normal crust structure. The problem lies in the fact that experiments conducted prior to 1975 used slope-intersection method to determine the velocities and the thickness of the crust. A study by Kennett and Orcutt (1976) showed that the uniform layer solution exhibits the minimum possible depth for a given velocity. In fact, White et al. (1992) indicated that application of the slope-intersection method resulted in the underestimation of the crustal thickness by approximately 20% when compared to synthetic seismograms modeling results. Additionally, interpretation techniques prior to the 80s (when the majority of the experiments in the western Atlantic were performed) did not consider amplitude variations of the crustal arrivals. Thus, the velocity models were based only on the travel-time fitting analysis. However, the most important factors contributing to scatter in the velocity structure observed in the western Northern Atlantic are the almost random location of the experiments relative to the fracture zone traces and the general roughness of the topography. Therefore, well controlled and precisely located experiments deserve special attention.

List of Figures

SITE 534

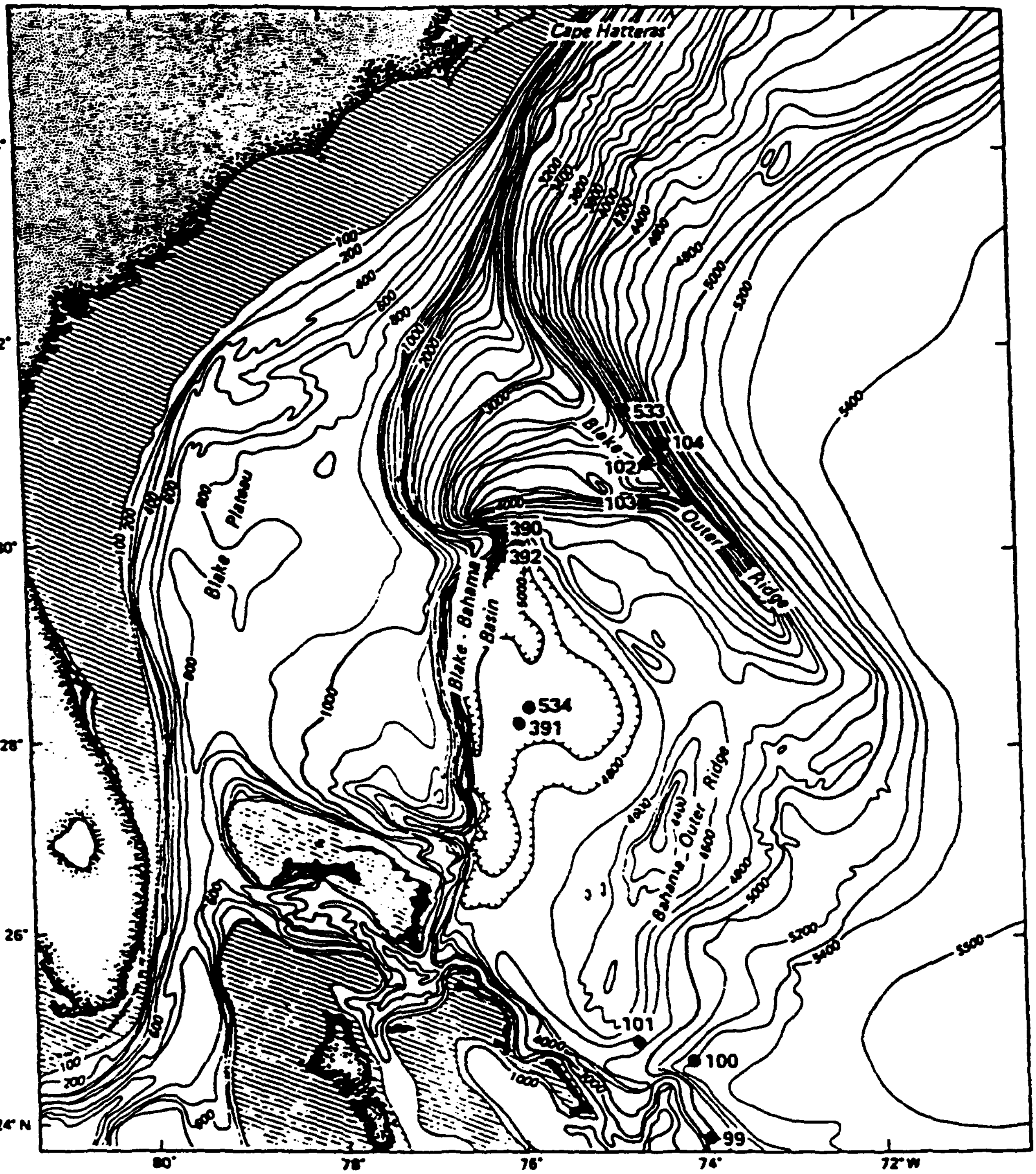


Fig. 1 Map of the LFASE Site.

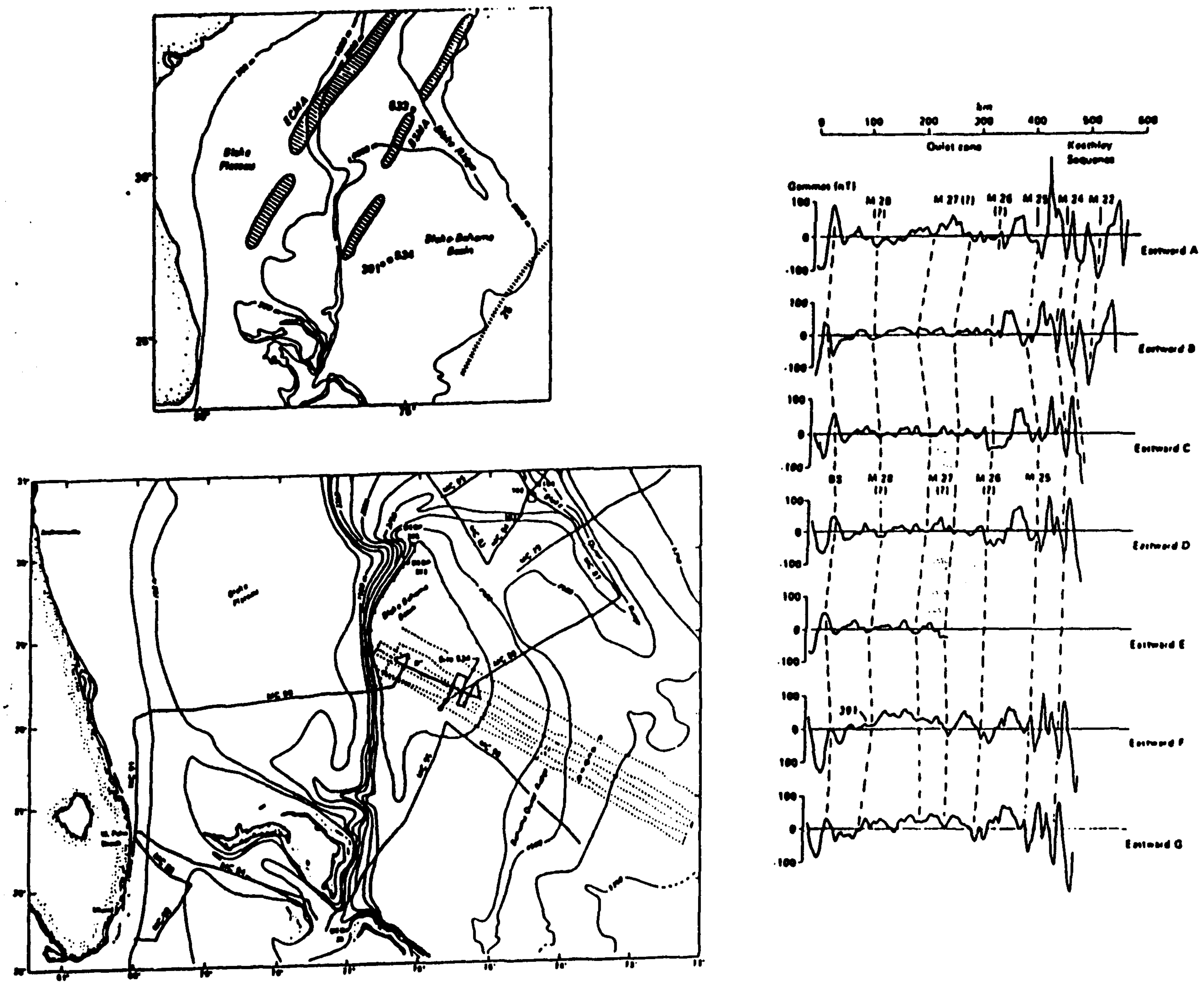
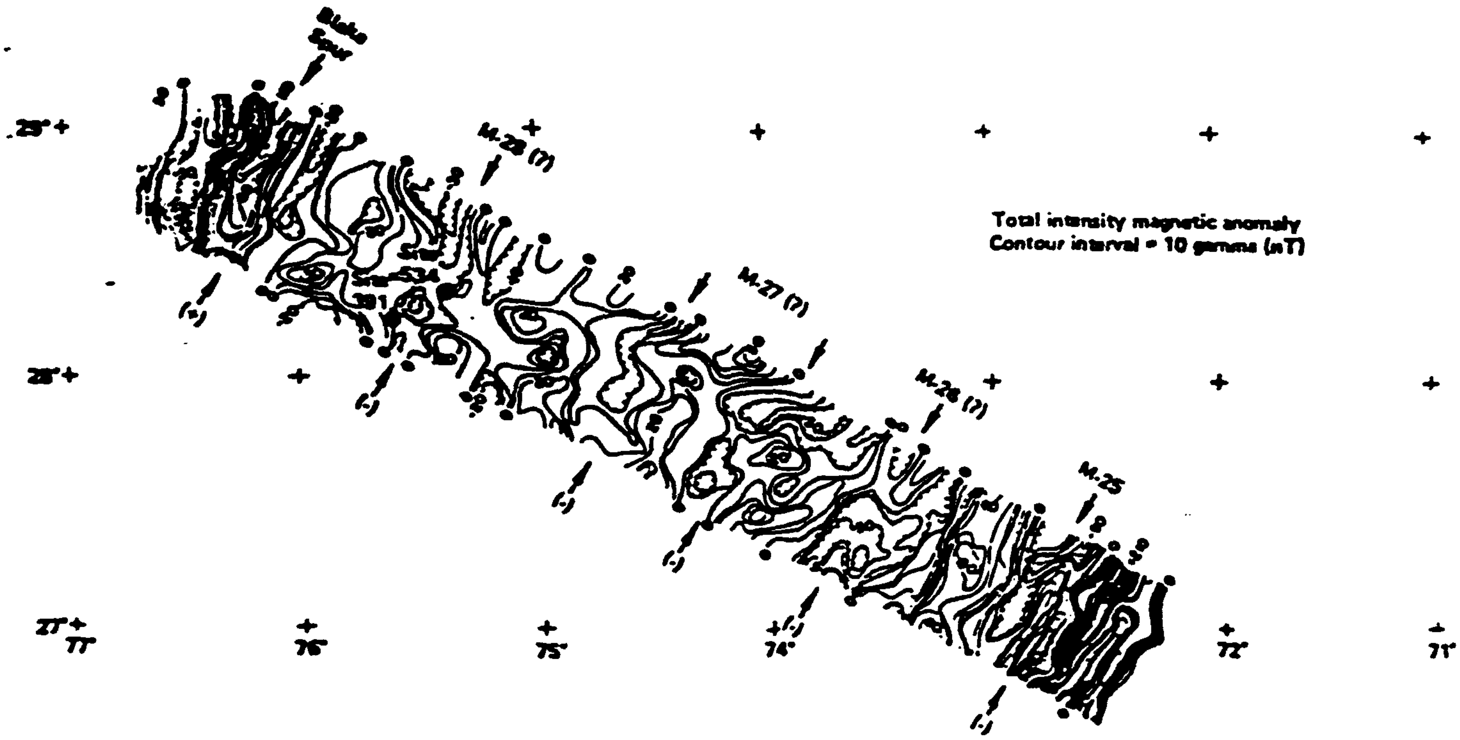


Fig. 2 Magnetic anomaly profiles across the Blake-Bahama Basin (after Bryan et al., 1980).



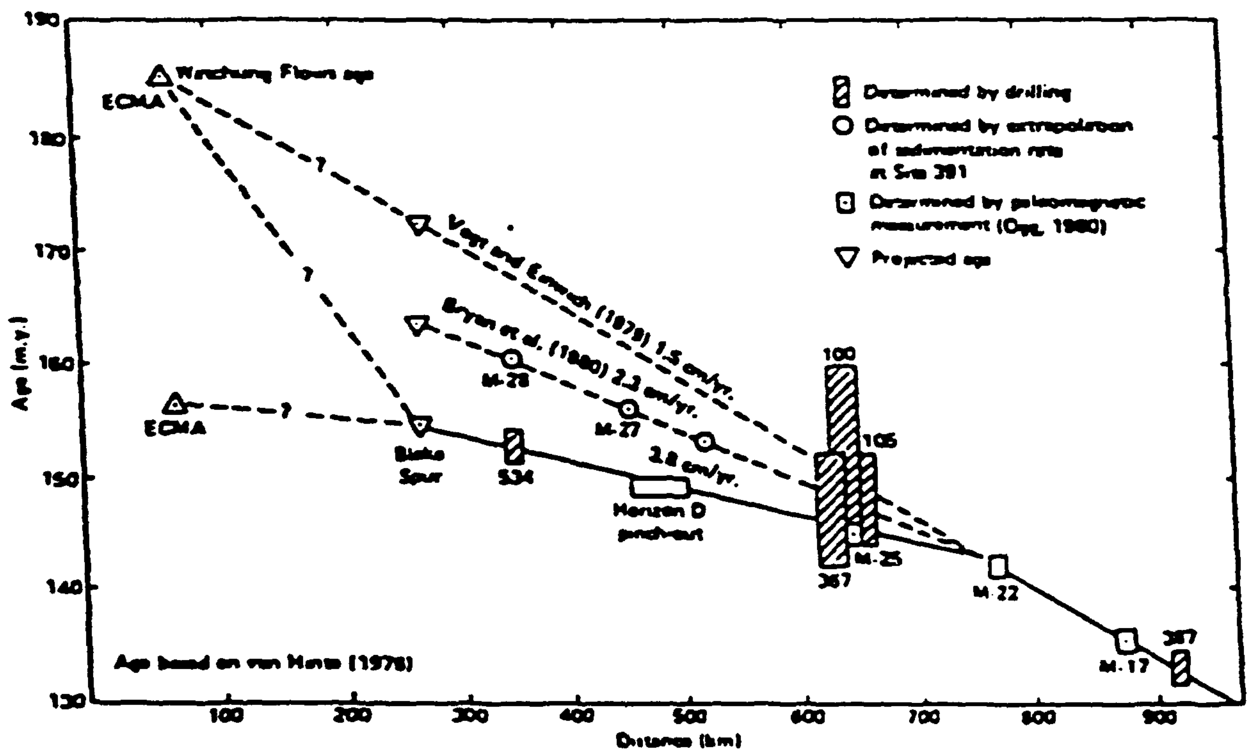


Fig. 3 Plot of age versus distance for key magnetic anomalies. Age of the lithosphere at the LFASE Site (near the DSDP 534 Borehole) was estimated to be 150-154 Ma.

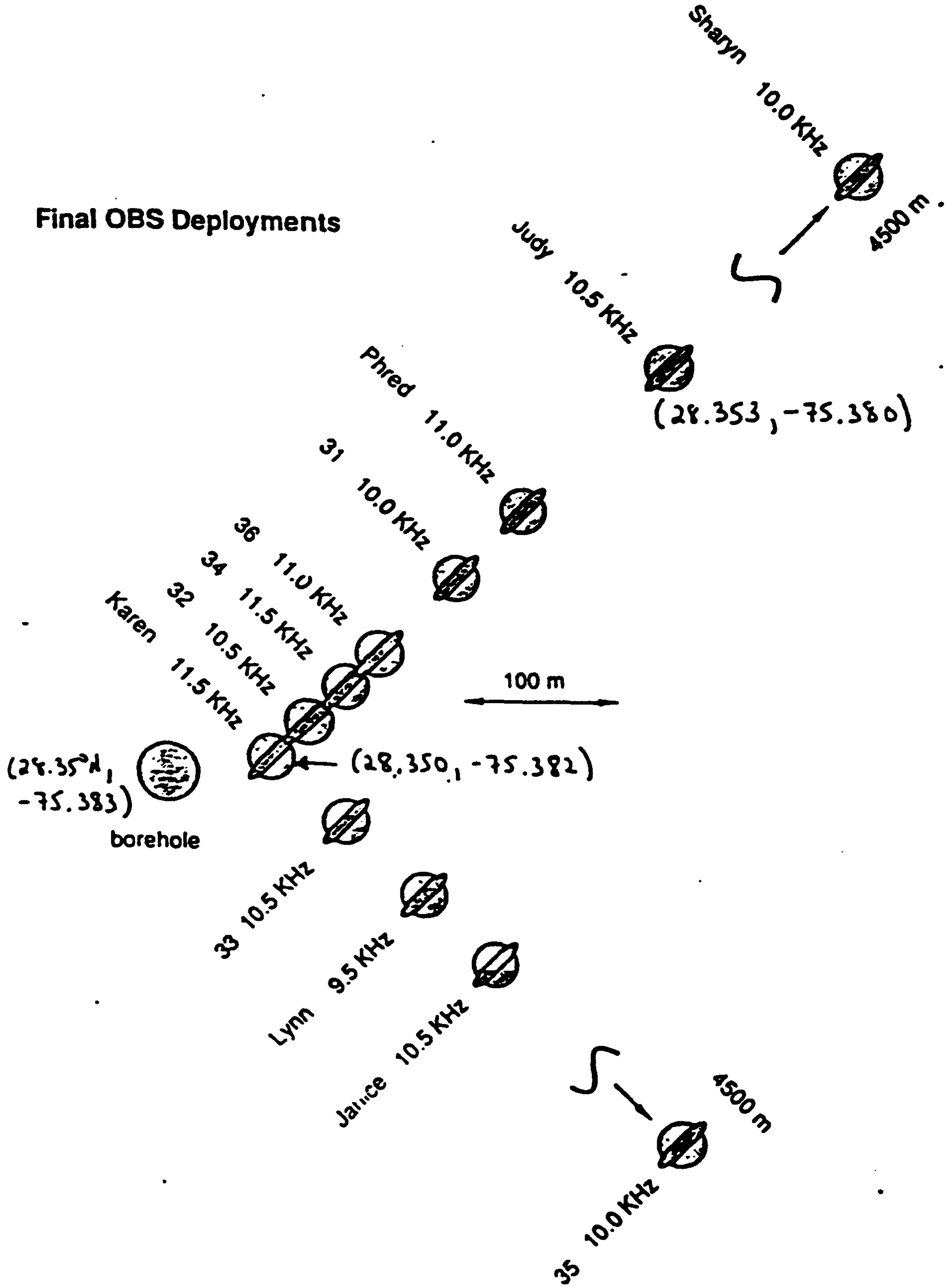


Fig. 4 OBS deployment configuration.

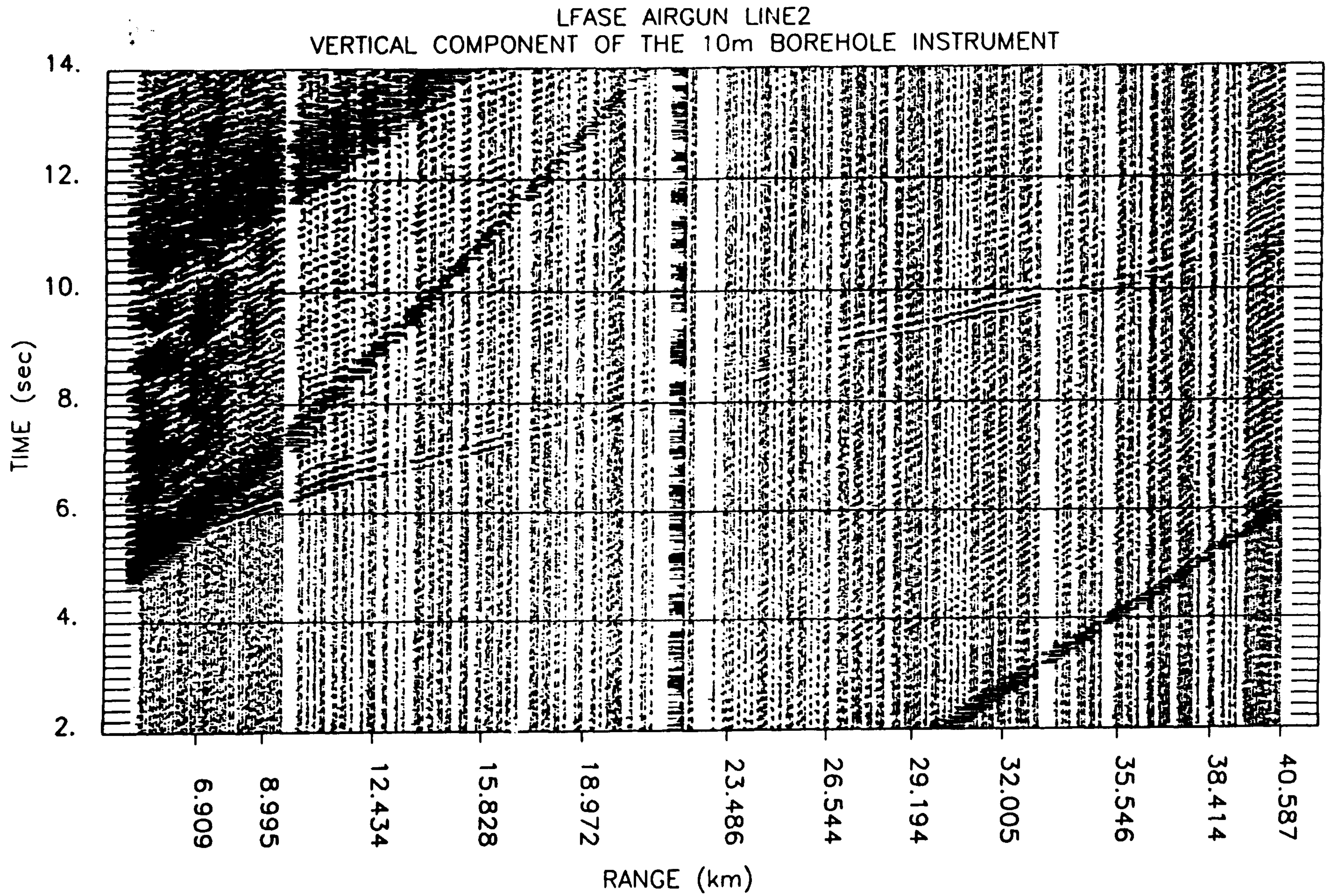


Fig. 5 Seismic section of the borehole instrument.

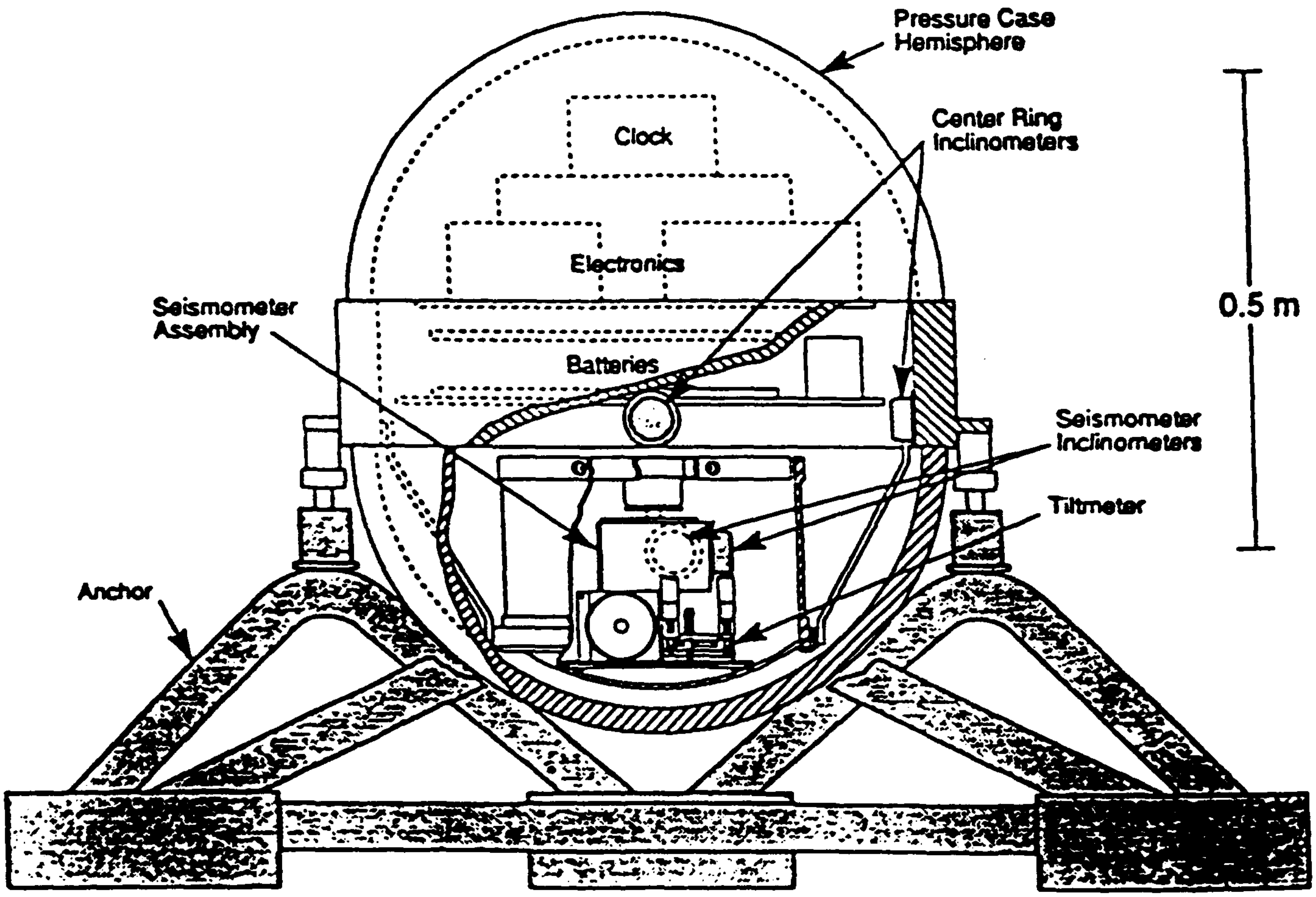


Fig. 6 Cross section of Sripps Ocean Bottom Seismometer.

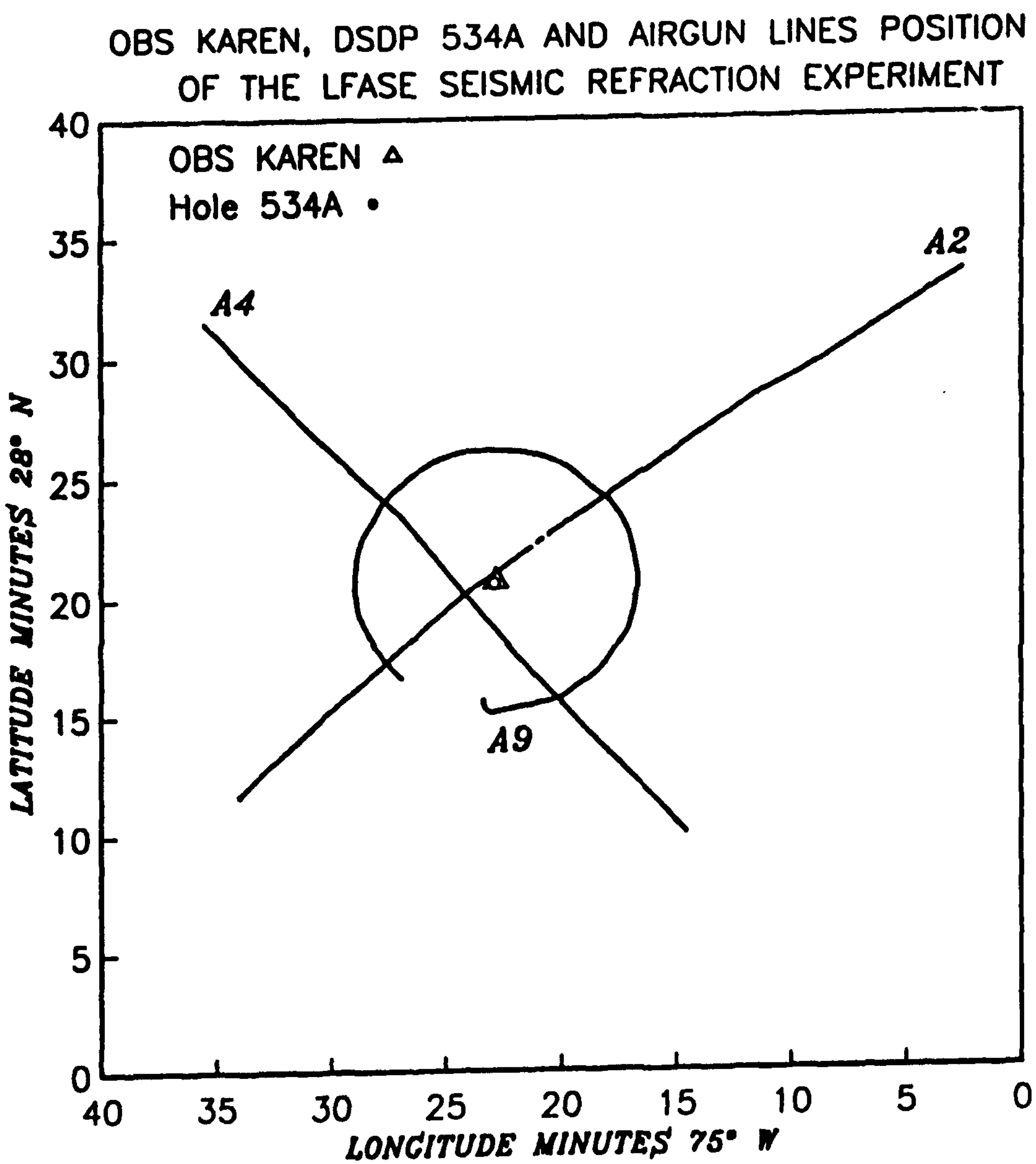


Fig. 7 Configuration of the airgun profiles.

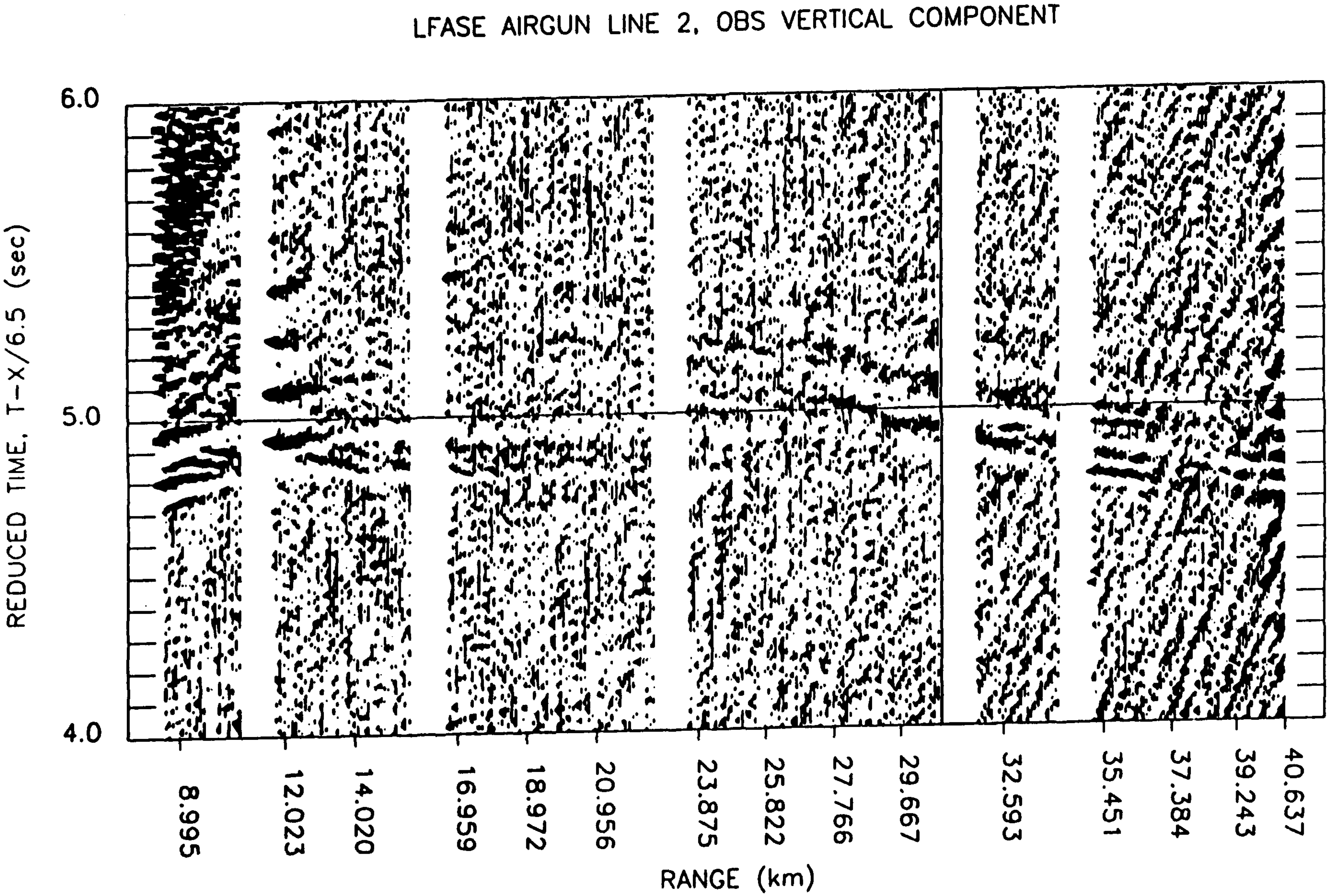


Fig. 8 Seismic section before filter application.

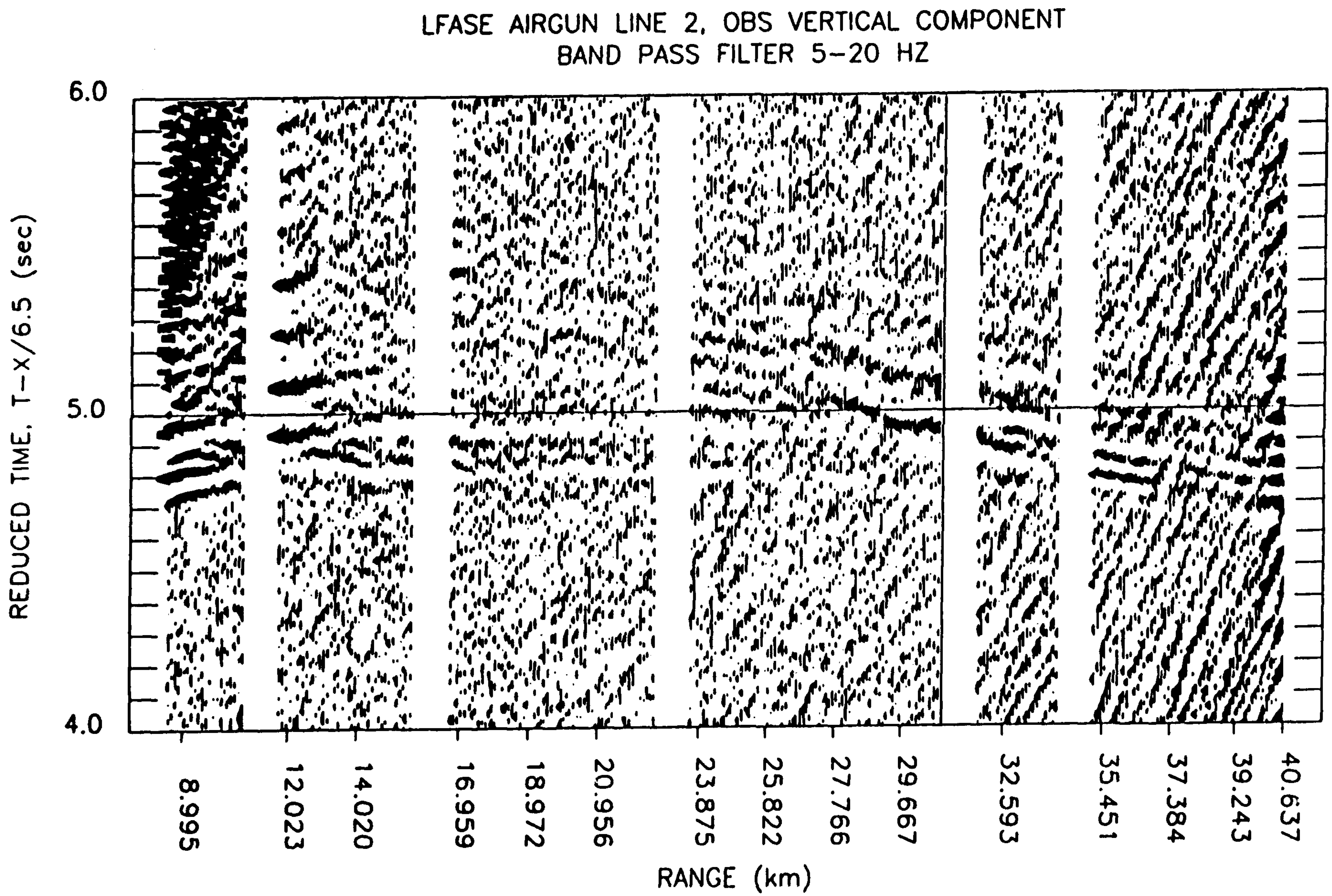


Fig. 9 Seismic section after application of the band-pass filter.

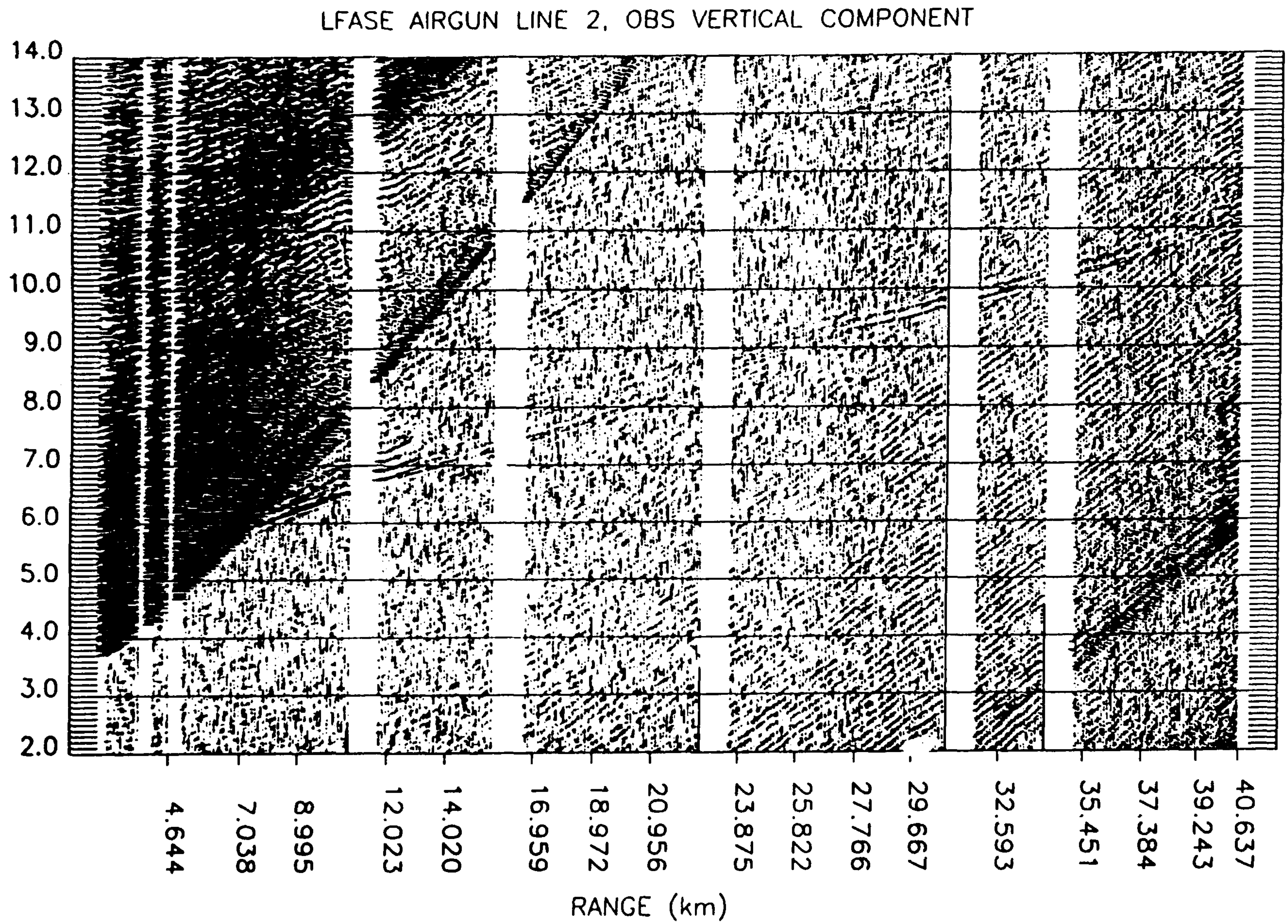


Fig. 10 Example of the raw data without reduction velocity and filter application.

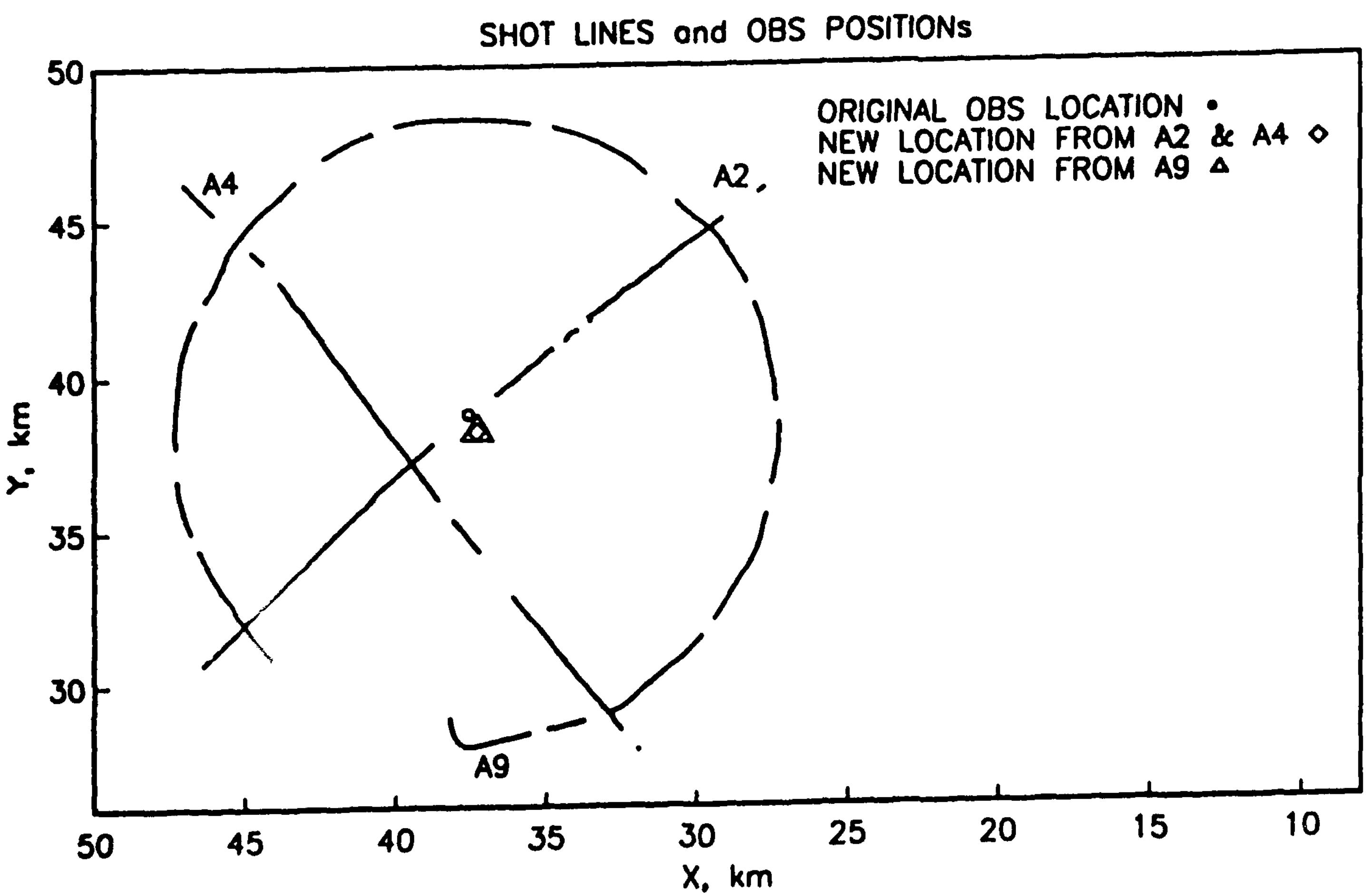


Fig. 11 Effect of navigation correction.

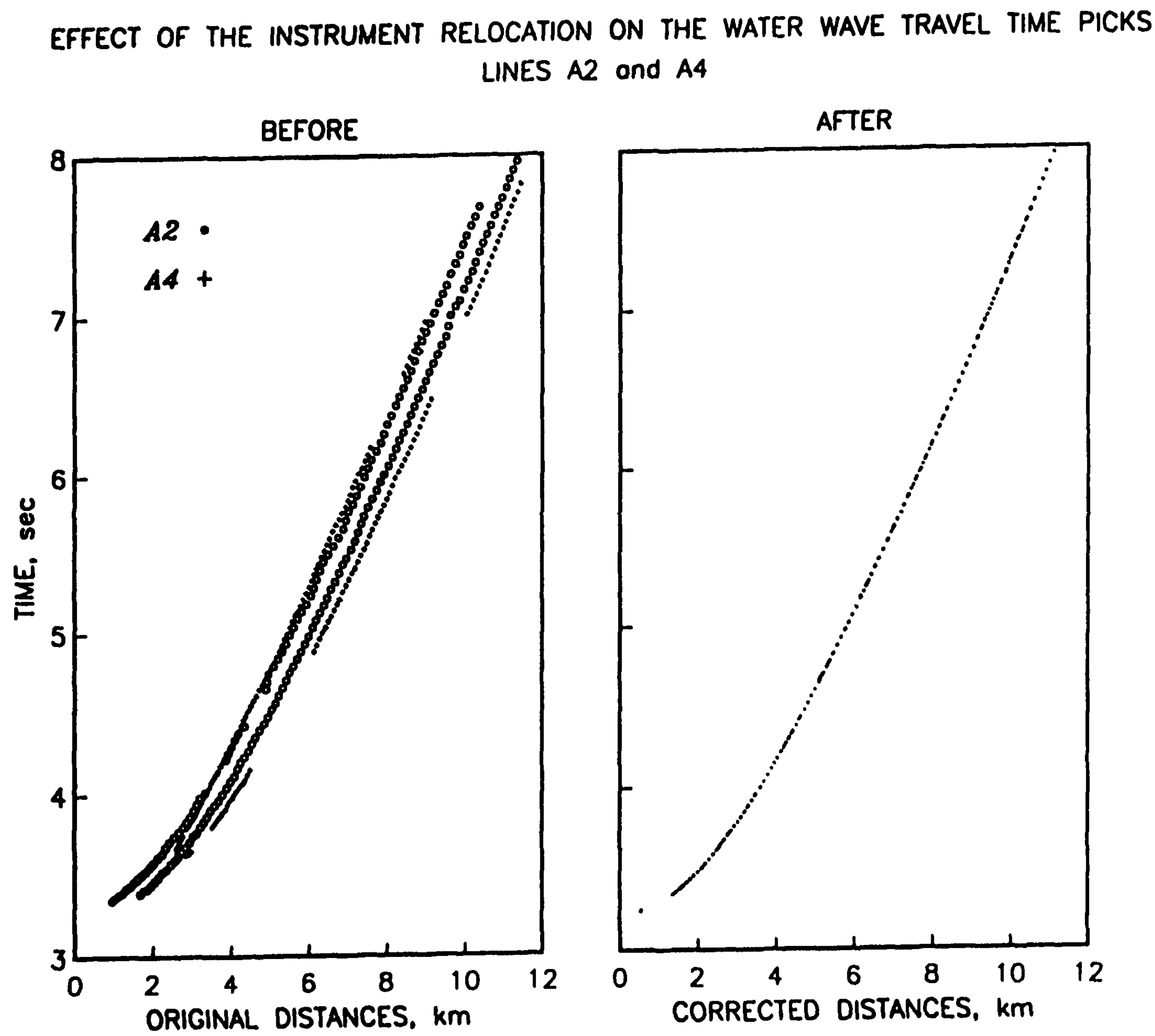
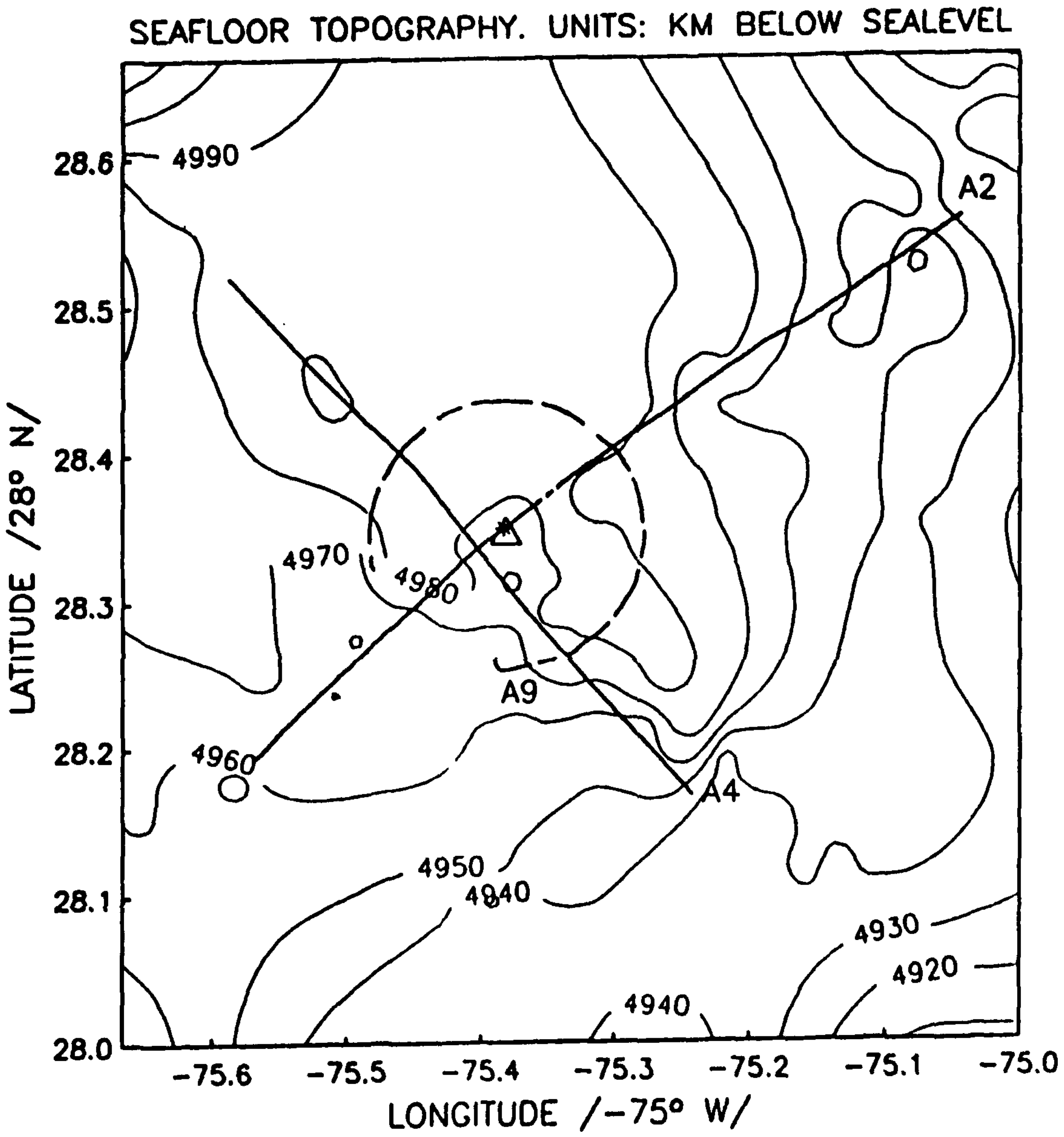


Fig. 12 Effect of the OBS relocation.
Comparison of the water-wave picks versus original and corrected ranges.



3.5kHz acoustic echo-sounder records corrected for water-column, interpolated by 2-D thin plate spline; 35 points in x and y

Fig. 13 Bathymetric chart.

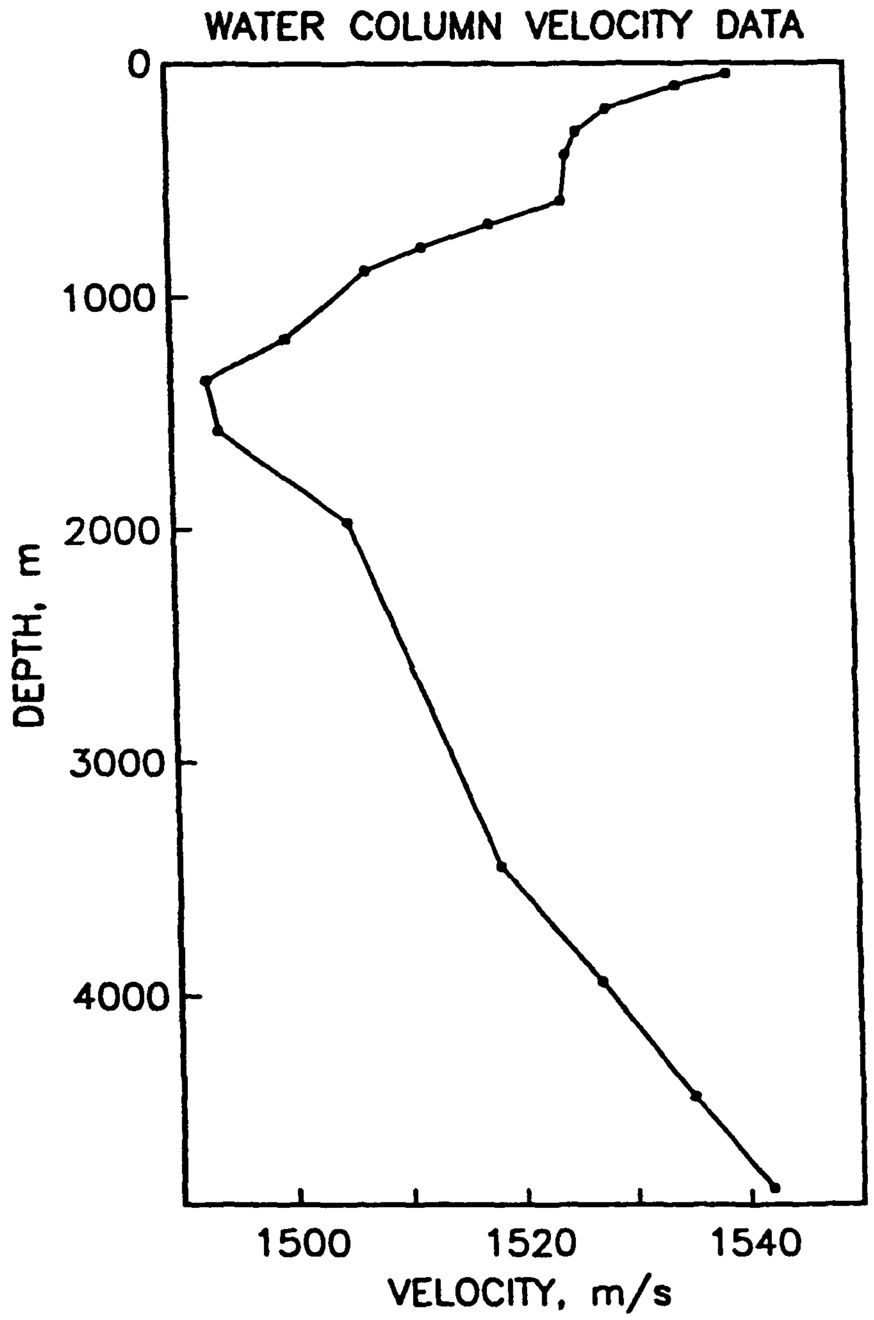


Fig. 14 Water wave velocity profile.

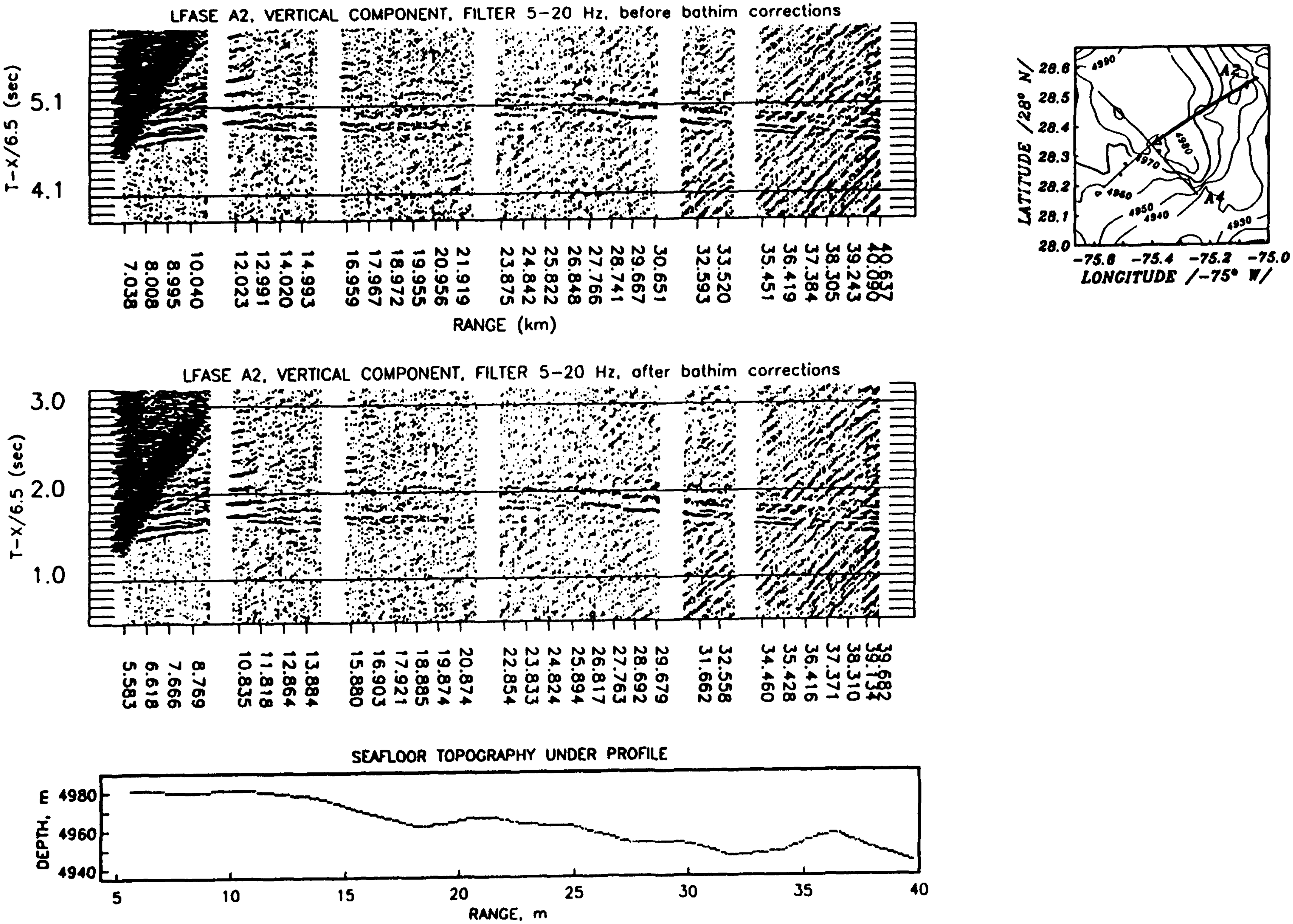


Fig. 15 Effect of the bathymetric correction.

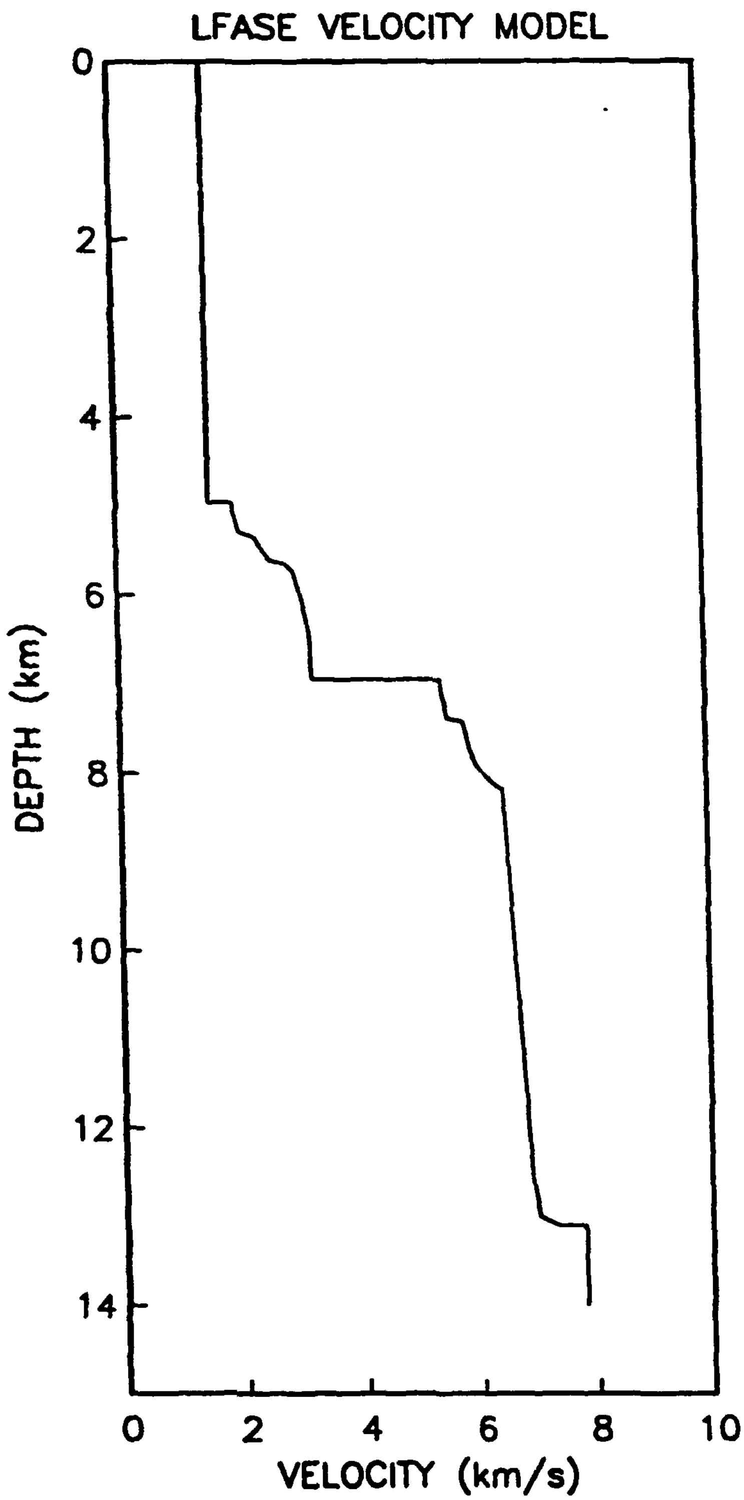


Fig. 16 Final velocity model.

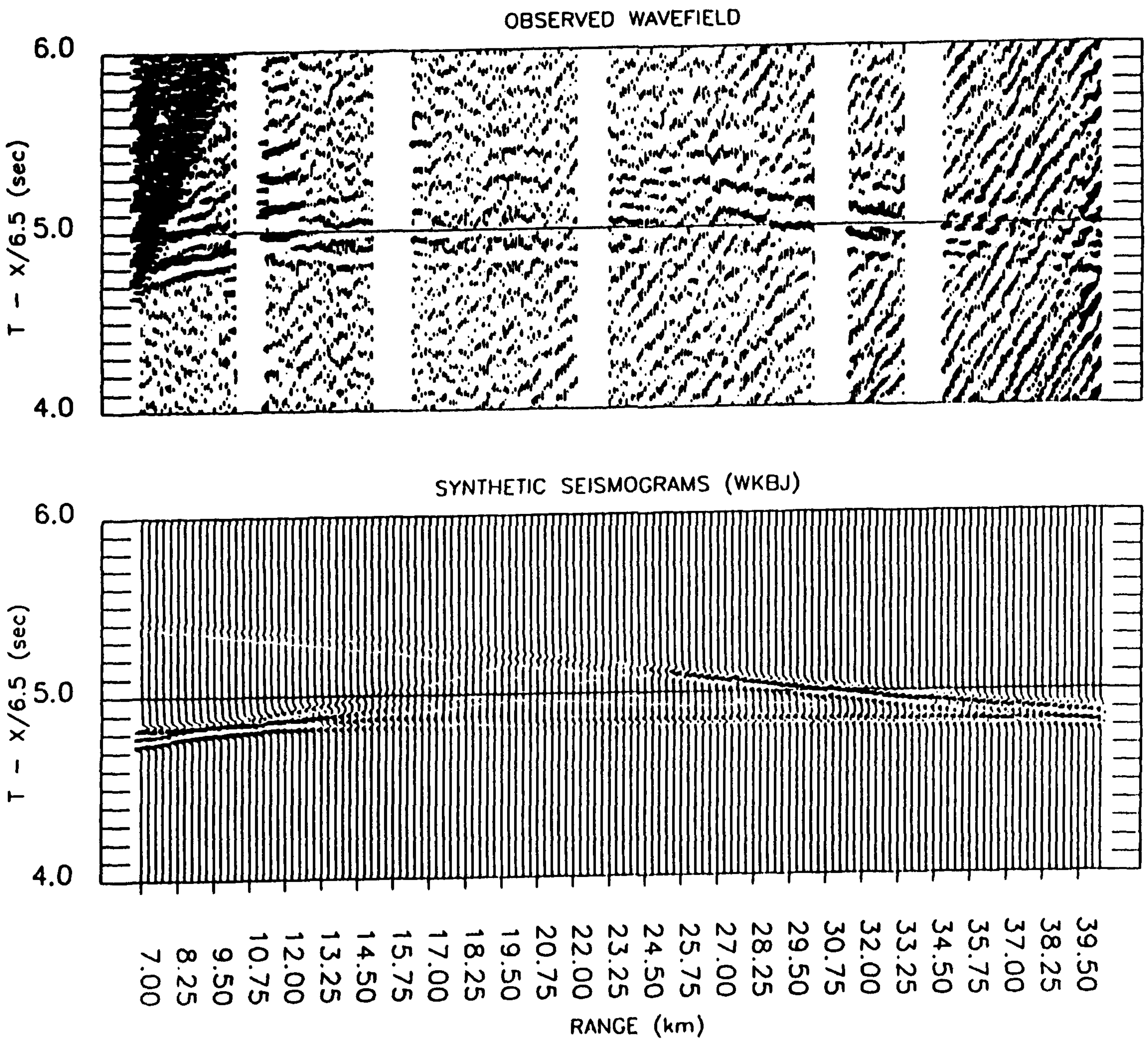


Fig. 17 Comparison between the real data and calculated synthetic seismograms.

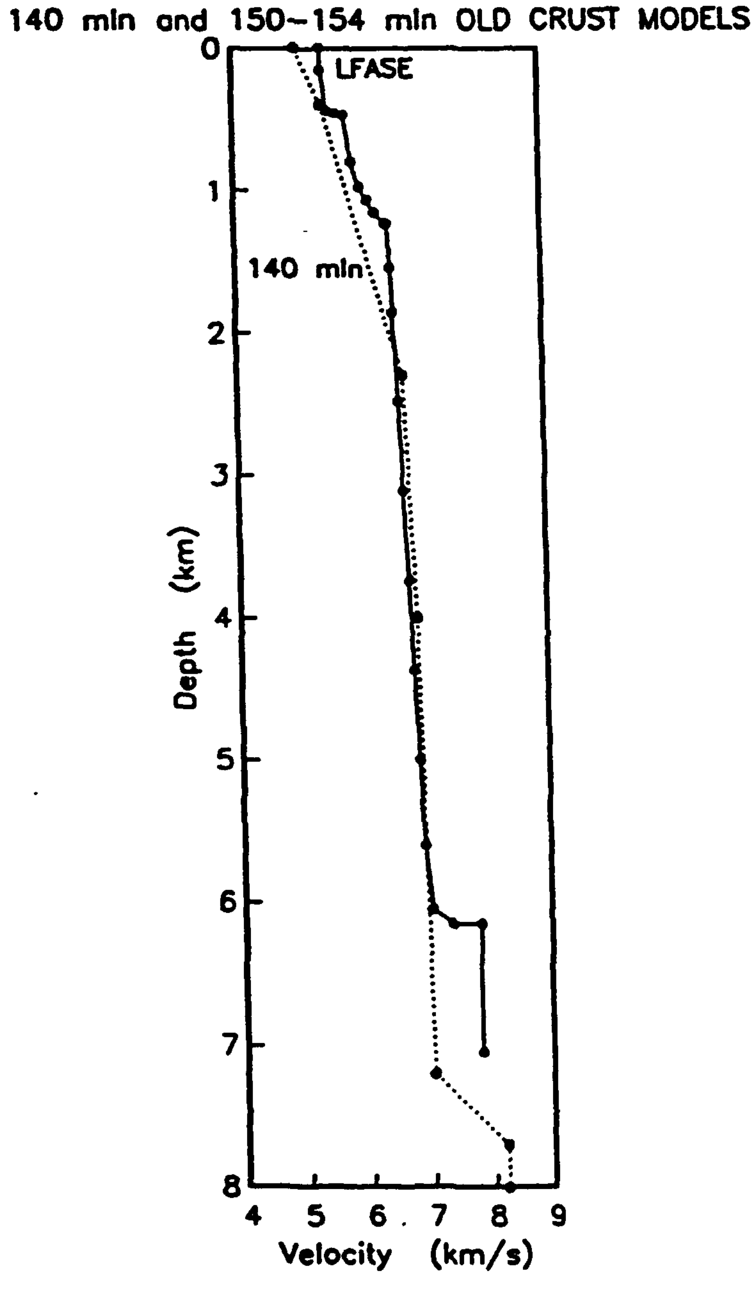


Fig. 18 Comparison between velocity models for 140 and 150-154 Ma old crust

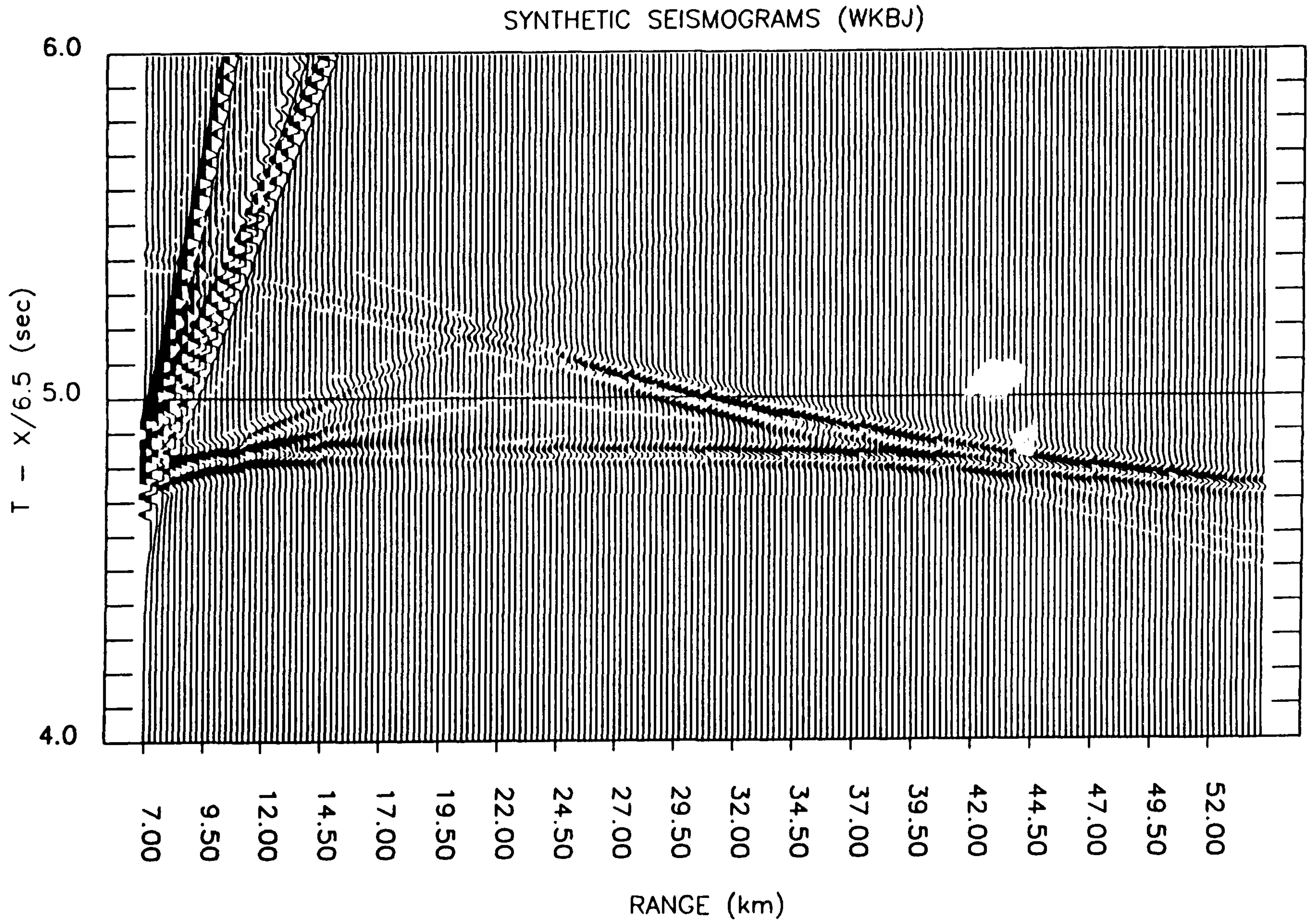


Fig. 19 Synthetic seismograms produced by our final velocity model.

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